AFOSR-TR-97

0548

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 7, 1997	3. REPORT TYPE AND DATES COVERED Final (July 1,95-August 31, 1997)

4. TITLE AND SUBTITLE
Fracture Mechanics of Brittle Matrix Composites with Imperfect Interfaces

5. FUNDING NUMBERS
F49620-95-1-0164

6. AUTHOR(S)
Autar K. Kaw (Compiler), P. Krishnan
H. Madonraj, J. Ye, G.H. Besterfield

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of South Florida
Mechanical Engineering Department
ENB 118,
Tampa, FL 33620-5350

8. PERFORMING ORGANIZATION REPORT NUMBER
2105-060-L0

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of Defense - Air Force
AFOSR/NA, Bolling AFB, DC 20332

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

19971103 064

11. SUPPLEMENTARY NOTES
AFOSR Technical Monitor - Walter F. Jones

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited   Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

In understanding the complexity of the fracture mechanics of brittle matrix composites, knowing reliable values of the mechanical properties of the fiber-matrix interface are important. Since all experiments designed to evaluate the mechanical properties of the fiber-matrix interface rely on curve fitting experimental measurements to analytical results, accurate physical modeling of these tests is imperative. In this report, two common tests, namely the push-in test and the slice compression test, were analytically simulated. In the push-in test, the effect of factors such as indentor shape, indentor size, push-through radius hole, and transverse isotropy of fibers on load-displacement curves was studied. All factors except the push through hole-radius were found to affect the load-displacement curves. In the slice compression test, comparison was made for the values of maximum protrusion, residual protrusion and debond lengths for a simple shear-lag analysis and a finite element analysis model. Large differences ranging from 15% to 70% were found by using the two different models. Hence, the importance of accurate modeling of the test cannot be ignored. The study also gives tools to an experimentalist for designing reliable experiments for evaluating reliable values of the mechanical properties of the fiber-matrix interface.

14. SUBJECT TERMS Brittle Matrix Composites, Interfaces, Push-in, Slice Compression	15. NUMBER OF PAGES 30
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102

DTIC QUALITY INSPECTED 3

FRACTURE MECHANICS OF BRITTLE MATRIX COMPOSITES WITH IMPERFECT INTERFACES

by

Autar K. Kaw
Principal Investigator
Mechanical Engineering Department
University of South Florida, Tampa, FL 33620-5350

Final Technical Report Submitted

to

Air Force Office of Scientific Research
AFOSR/NA
Washington, DC 20332
Dr. Walter F. Jones, Monitor

Award Number: F49620-93-1-0164

October 6, 1997

FRACTURE MECHANICS OF BRITTLE MATRIX COMPOSITES WITH IMPERFECT INTERFACES

by

Autar K. Kaw
Principal Investigator
Mechanical Engineering Department
University of South Florida, Tampa, FL 33620-5350

Final Technical Report Submitted

to

Air Force Office of Scientific Research
AFOSR/NA
Washington, DC 20332
Dr. Walter F. Jones, Monitor
Award Number: F49620-95-1-0164

October 6, 1997

ACKNOWLEDGMENT

I thank the AFOSR for supporting this grant. The support, confidence in my technical abilities and encouragement of AFOSR grant monitor, Dr. Walter Jones is deeply appreciated. I am grateful for the time and discussions with Dr. N.J. Pagano of WPAFB, Ohio. I also thank Dr. G.P. Tandon for our informal discussions about the project and providing numerical results for comparative purposes. The strong financial support of the Department of Mechanical Engineering, the College of Engineering and the Division of Sponsored Research in providing matching fund for the project is acknowledged.

ABSTRACT

In understanding the complexity of the fracture mechanics of brittle matrix composites, knowing reliable values of the mechanical properties of the fiber-matrix interface are important. Since all experiments designed to evaluate the mechanical properties of the fiber-matrix interface rely on curve fitting experimental measurements to analytical results, accurate physical modeling of these tests is imperative.

In this final report, two common tests, namely the push-in test and the slice compression test, were analytically simulated. In the push-in test, the effect of extrinsic factors such as indentor shape and size, and push-through radius hole, and intrinsic factors such as transverse isotropy of fibers on load-displacement curves was studied. All factors except the push through hole-radius were found to affect the load-displacement curves.

In the slice compression test, comparison was made for the values of maximum protrusion, residual protrusion and debond lengths for a simple shear-lag analysis and a finite element analysis model. Large differences ranging from 15% to 70% were found by using the two different models. Hence, the importance of accurate modeling of the test cannot be ignored. It also shows that there is a need for further study in this area to synergize the experimental and analytical tools required to find the mechanical properties of the fiber-matrix interface. The study also gives tools to an experimentalist for designing reliable experiments for evaluating reliable values of the mechanical properties of the fiber-matrix interface.

TABLE OF CONTENTS

INTRODUCTION

The advantages of using ceramics are their high refractoriness and strength, low density, excellent corrosion and oxidation resistance, and low cost. However, their brittle nature and low fracture toughness makes them prone to catastrophic failure. A promising method to overcome these shortcomings is by reinforcing ceramics by aligned continuous fibers, such as, silicon carbide and carbon. The resulting composite materials are called ceramic matrix composites (CMCs), and have increased fracture toughness and fail more gracefully. However, they are highly anisotropic and fail in a complex manner, and often do not follow the basic concepts of fracture mechanics. So, the basic understanding and modeling of the mechanics of these materials are essential for the development of these materials.

In this study, two common tests used to find the values of the mechanical properties of the fiber-matrix interface were theoretically simulated. Accurate modeling of these tests is especially critical as experimental measurements are curve fitted to analytical models to evaluate the mechanical properties of the fiber-matrix interface. For example, in one of the two tests simulated here, namely, the push-in test, the experiment measures the load vs. displacement data. Simplified analytical models develop load-displacement curves as a function of mechanical properties of the constituents, fiber volume fraction, and fiber-matrix properties - coefficient of friction and residual stresses. Knowing the mechanical properties of the

constituents and the fiber volume fraction, one can regress to find the coefficient of friction and residual stresses at the fiber-matrix interface. ***Although simple analytical models are easy to use, are they accurate for finding values for the two interface mechanical properties***? This is the central theme of this work and is discussed under Task 1 and Task 2 of this final technical report.

All of the work done in this grant is available in thesis and refereed journals. The titles, abstracts and their references are given in Appendix A. The cumulative list of researchers is given in Appendix B. We give a comprehensive executive summary of the significant work accomplished in this grant in the next section.

TASKS

Task 1: Effect of Extrinsic and Intrinsic Factors on an Indentation Test

The interface is a vital part of the ceramic matrix composite in determining its strength and toughness. Hence quantitative value of the mechanical properties of the interface between the fiber and matrix is of great importance. However, all experiments designed to find these values rely on curve fitting the experimental measurements to theoretical models. Hence the reliability of the obtained mechanical properties of the interface is dependent on the accuracy of the theoretical models.

One of the tests conducted for the measurement of the mechanical properties of the interface is the push-out test (Figure 1). Several analytical models have been developed for the test and they range form simple analytical models based on shear-lag assumptions (Shetty, 1988) to more physically realistic finite element models (Shirazi-Adi, 1992). However, the effect of extrinsic and intrinsic factors on the push-out test has not been studied. These factors include the following:

Extrinsic Factors

1. Shape (smooth, flat and pointed) of indentor (Figure 2)
2. Size (contact radius to fiber radius ratio) of indentor
3. Radius of the push-through hole

Intrinsic Factors

1. Relative elastic moduli of fiber and matrix

2. Material symmetry (Isotropic vs. Transversely Isotropic) of fiber

Both analytical (Figure 3) and finite element models (Figure 4) (Maze, 1983; Nike-2D, 1991; Orion, 1985) were used to understand the effect of the above factors. In the analytical model, a semi-infinite circular fiber is bonded to a half-space matrix. The fiber and matrix are assumed to have identical mechanical properties and the interface either is perfectly bonded or follows the Coulomb friction law. The finite element geometry extends the above model to fiber and matrix of finite length and radius.

The following conclusions were drawn from the various studies:

- The indentation test is not affected by the radius of the push-through hole
- The displacements, slip lengths and stresses for the flat indentor case are more than that in the uniform pressure case (Figure 5). Also, the axial displacement between the fiber and the matrix increases as the radius of the indentor increases (Figure 6). Since this is one of the experimental measurements, the shape and radius of indentor should be dealt in the curve fitting of the indentation tests.
- Assuming a transversely isotropic fiber to be isotropic is not suitable as the load vs. fiber-matrix interface displacements vary substantially (Figure 7).

Task 2: Simulation of the Slice Compression Test

This task also concerns the need for accurate modeling of theoretical models for reliable calculation of mechanical properties of the fiber-matrix interface. In this study, the slice compression test (Shafry, et al 1989, Shafry and Brandon, 1991) (Figure 8) is simulated to find the effect of using approximate techniques, such as, shear-lag analysis to model the test. This is important as slice compression test like the indentation test does not directly evaluate the mechanical properties of the fiber-matrix interface. If the analytical model used to regress the experimental data to find the mechanical properties of the interface is questionable, the results themselves are not reliable either.

In contrast to the push-in test of Task 1, the slice compression test can be used to extract interfacial properties where a large number of fibers are tested simultaneously. In this test, a thin slice of unidirectional aligned composite (about 2mm thick) is cut normal to the fiber direction and the opposite flat faces are polished (Figure 8). This slice is then compressed between a soft top plate (typically made of aluminum or copper alloys) and a hard bottom plate (typically made of silicon nitride). The loading on top of the aluminum plate is slowly increased to a peak value, and then unloaded completely.

On loading the specimen, at sufficiently high loads, debonding is initiated at the top surface of the specimen between the fiber and matrix (Figure 8). This causes

the stiffer component (usually the fibers in ceramic matrix composites) to protrude into the aluminum plate. This creates a negative impression on the soft aluminum. On unloading, the fibers relax partially back into the matrix, thus leaving a residual protrusion of the fibers.

Since aluminum is very plastic, the depth of the indentation on the aluminum plate is usually taken as equal to the maximum protrusion of the fibers at maximum load. The maximum and the residual protrusion are measured in this test using scanning electron microscopes.

The quantities thus obtained have to be related to the interfacial parameters, namely the coefficient of friction and residual stresses. For this purpose a mathematical model of the test is required (Figure 9). Analytical studies have been made of the slice-compression test by several authors (Lu and Mai, 1994 and Hseuh, 1993). All models are based on shear-lag analysis. Hence there was a need to develop a physically more realistic model such as based on finite element analysis.

In this task, the slice compression test loading is modeled in two ways: a) by distributing the overall load on the top plate by using unequal but uniform loads on the fiber and matrix as done in shear-lag models, b) by modeling the top plate as elastoplastic and applying a uniform pressure to it. The maximum and residual protrusions, and debond lengths are then compared between the finite element and shear-lag analysis models for both cases of loading. The effect of finite modulus of the base plate on the protrusions obtained, and the distribution of pressure on the

surface of the fiber and matrix on loading the aluminum plate is also studied.

The conclusions drawn from the studies were:

- The three measurements - maximum protrusion, residual protrusion and debond length are highly dependent on the modeling technique. Differences occur anywhere from 10 to 70% between the finite element and shear-lag models (Figures 10-12).
- Assuming the base plate as non-rigid made a difference of 15% in some of the above measurements (Figure 13).
- Assuming uniform stresses on the top surface of the fiber and matrix is not valid (Figure 14). Even the average stresses on the fiber and matrix found by directly applying the stresses to the top plate differed by as much as 25% with the shear-lag models.

All the above results show that slice compression tests need to be regressed to models which are physically more realistic. Since the results of the slice compression test do not directly give the values of the coefficient of friction and residual stresses, but by regressing it to an analytical model, any trust in such values needs to be verified. Clearly shear-lag and finite element models give quite different responses. Although the former model explicitly gives the values of the two mechanical properties of the interface from the three experimentally measured values of maximum protrusion, residual protrusion and debond length, the same

cannot be said about finite element models. So further study is required in this area to come up with a reasonably acceptable analytical model for regressing to find these interface properties.

Both the above studies are critical in the ongoing Air Force effort to characterize brittle matrix composites for use in high temperature applications such as jet engines. Developing confidence in the experimental and analytical characterization of brittle matrix composites are prerequisites to a reliable and optimum design of components made of such advanced composite materials.

REFERENCES

Hsueh, C-H. (1993), Analysis of slice compression tests for aligned ceramic matrix composites. *Acta Metallurgica Materialia*, 41, 3585 - 3593.

Lu, G-Y. and Mai, Y-W. (1994), A theoretical model for the evaluation of interfacial properties of fiber-reinforced ceramics with the slice compression test. *Composite Science and Technology*, 51, 565 - 574.

Maze: (1983), An input generator for DYNA2D and NIKE2D. Lawrence Livermore National Laboratory.

Meda, G., Hoysan, S. F., and Steif, P. (1993), The effect of fiber Poisson expansion in micro-indentation tests. Journal of Applied Mechanics, 60, 986-991

NIKE-2D: (1991), A nonlinear, implicit, two-dimensional finite element code for solid mechanics - user manual. Lawrence Livermore National Laboratory.

ORION: (1985), An interactive color post-processor for two dimensional finite element codes. Lawrence Livermore National Laboratory.

Shafry, N., Brandon, D. G. and Terasaki, M. (1989), Interfacial friction and debond strength of aligned ceramic matrix composites. *Euroceramics*, 3.453 - 3.457.

Shafry, N. and Brandon, D. G. (1991), Interfacial friction and debond strength of

aligned ceramic matrix composites. *Advanced Structural Inorganic Composites*, 6, 109 - 118.

Shetty, D. K. (1988), Shear-lag analysis of fiber pushout (indentation) test for estimating interfacial frictional stress in ceramic-matrix composites. *Journal of American Ceramic Society*, 71, C107-C109.

Shirazi-Adi, A. (1992), Finite element stress analysis of a push-in test - Part I: Fixed interface using stress compatible elements. *Journal of Biomechanical Engineering*, 114, 111-118.

Appendix A. ABSTRACT OF PUBLISHED JOURNAL PAPERS

Title: **Effect of Extrinsic and Intrinsic Factors in Indentation Tests**

Authors: **T. Srinath, H. Madanraj, A.K. Kaw, J. Ye and G.H. Besterfield**

Journal: **International Journal of Solids and Structures, Vol. 33, No. 24, pp. 3497-3516, (1996).**

Abstract : The effect of extrinsic and extrinsic factors on measured results, such as load-displacement curves and interfacial stresses, from indentation tests of composite materials is studied using both analytical and finite element models. The intrinsic factors include properties of the fiber-matrix interface and the material symmetry of the fiber (transversely isotropic or isotropic). The extrinsic factors include the radius of the hole through which the fiber is pushed in, and the size and shape of the indentor. Out of the above factors, only the radius of the hole has negligible effect on the results of the indentation test.

Title: **Should We Continue to Debate over the Change to SI System?**

Authors: **A.K. Kaw and M. Daniels**

Journal: **<u>Journal of Professional Issues in Engineering Education and Practice</u>, Vol. 122, No. 2, pp. 69-72, (1996).**

Abstract: Ninety five percent of the world's population uses the international system of units - Systeme International (SI). However, we continue to debate our country converting to the international system of units. In this paper, we have presented a comprehensive list of the advantages of the SI system. We then give the reasons why we need to convert to the SI system of units. A few major corporations in USA have already made the changeover to the SI system, but the general population is still reluctant to make the change from the US customary units. Studying these conflicting issues simultaneously is important in the implementation of the SI system, if enforced in our country. We have also enumerated the ways we can progress toward the changeover. These ways include learning from the experiences of our own failed effort of the Metric Conversion Act of 1975 and study how other countries made the successful changeover in recent decades.

APPENDIX B. CUMULATIVE LIST OF RESEARCHERS

The following students were involved in the research under this grant. Their thesis titles are given below and are available from

University of South Florida Library,

LIB 128, 4202 E. Fowler Avenue,

Tampa, FL 33620.

K. Gangakhedkar, "Effect of Fiber Volume Fraction on Mechanics of Multiple Cracking in Fiber Reinforced Composites", December 1995 (MS).

H. Madanaraj, "Finite Element Model of Push-in Test for Composite Materials", December 1995, (MS).

P. Krishnan, "Simulation of a Slice Compression Test in Ceramic Matrix Composites," December 1996, (MS).

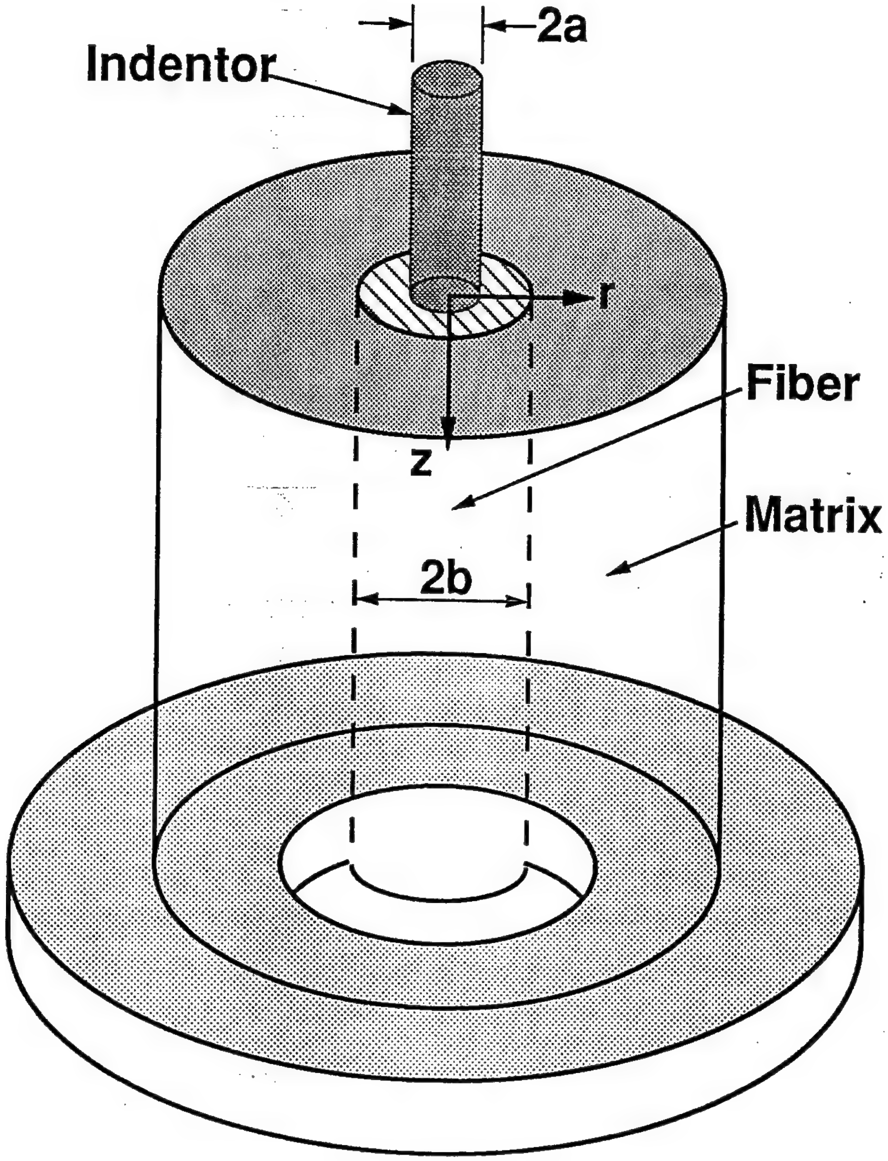

Figure 1. Composite Specimen on an annular platform for an indentation test.

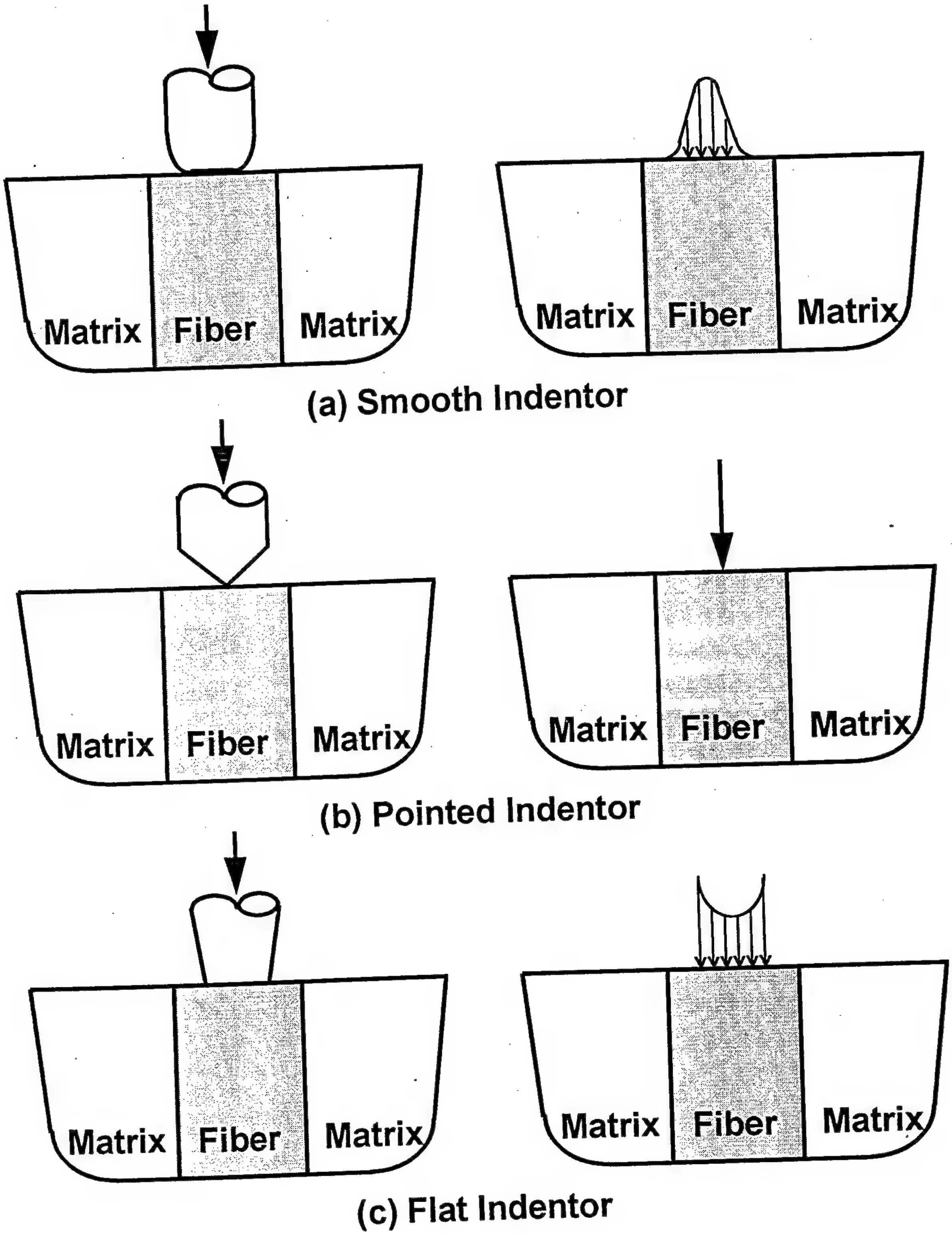

Figure 2. Various indentor geometries and the approximated pressure distribution on the fiber.

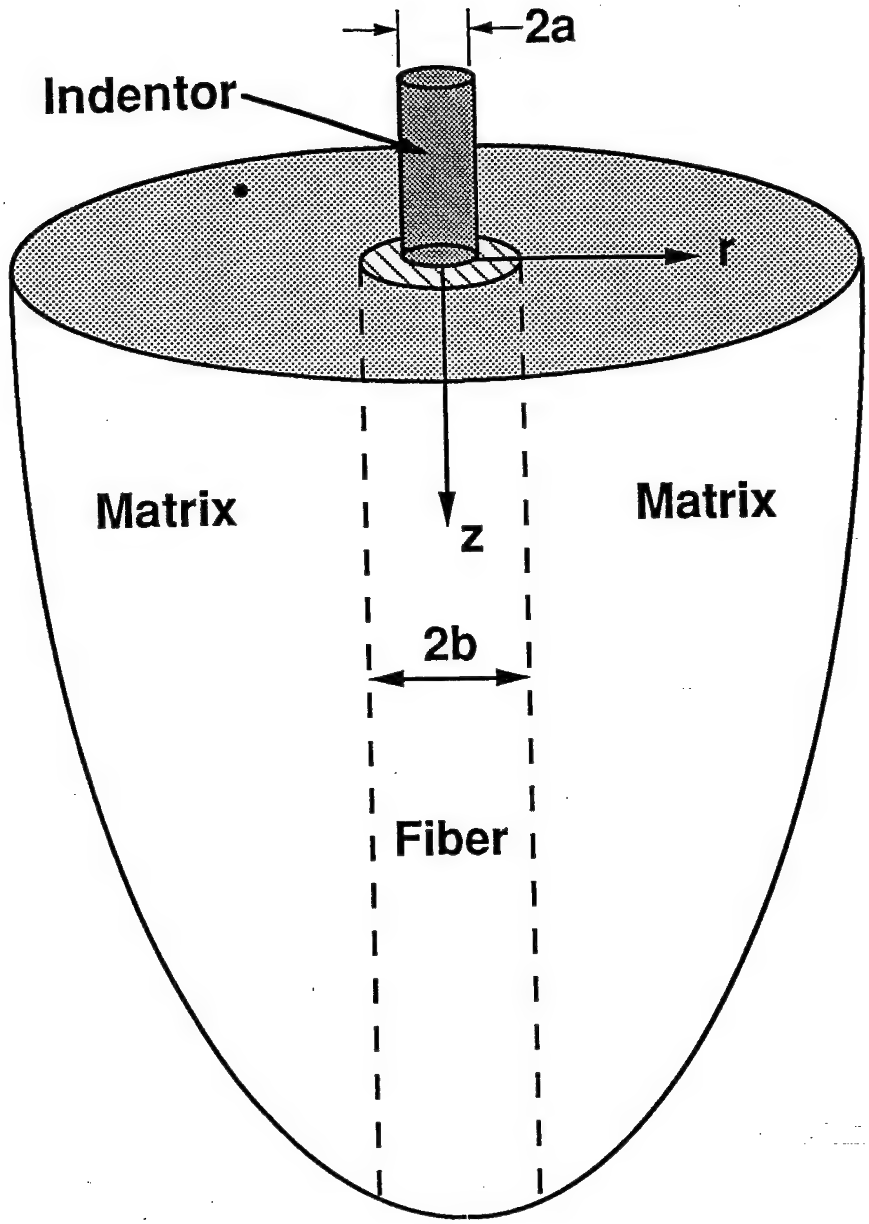

Figure 3. Circular fiber embedded in an infinite half-plane under an indentor load.

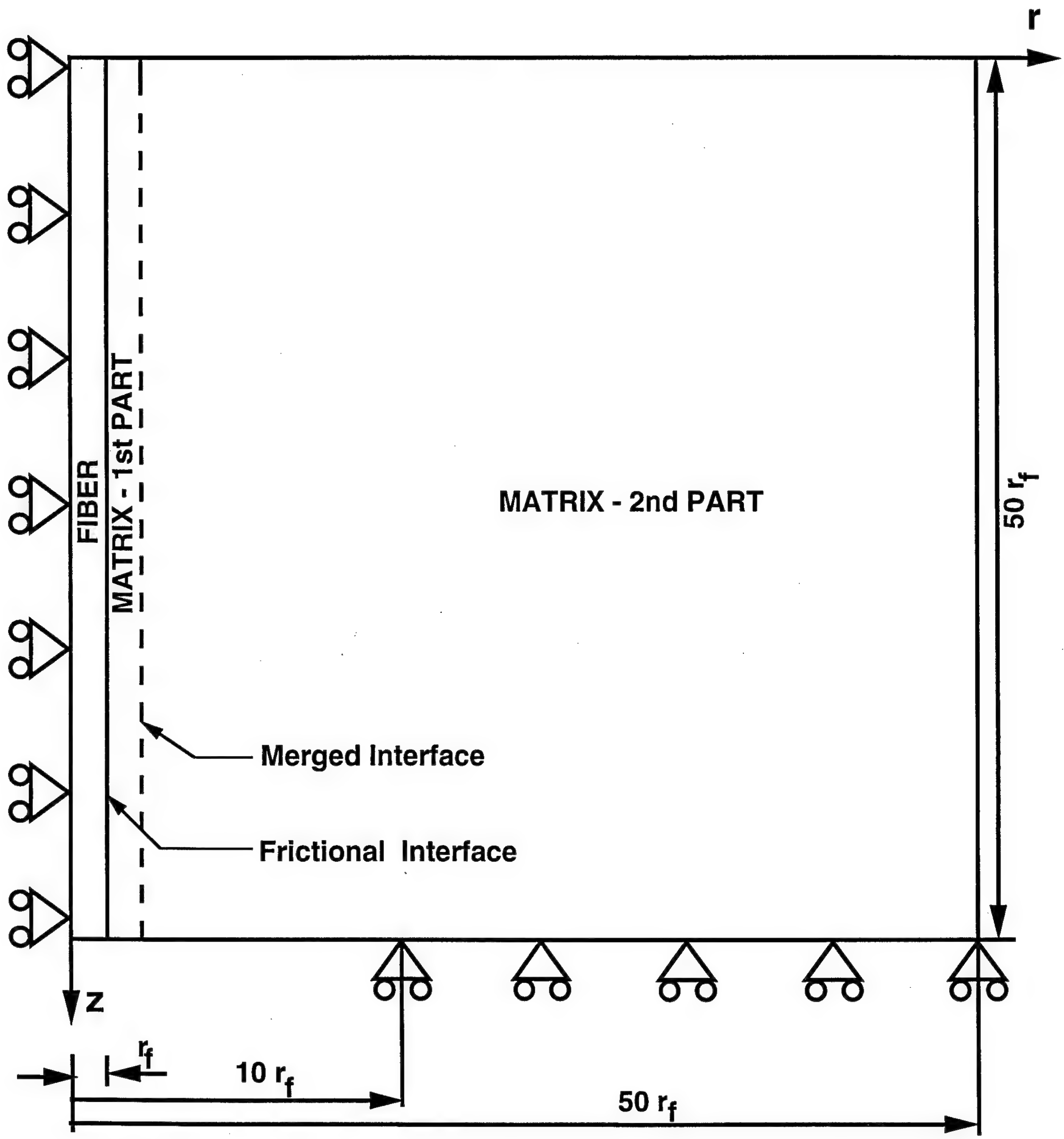

Figure 4. Finite element model with boundary conditions and external pressure acting on the matrix for finite element results.

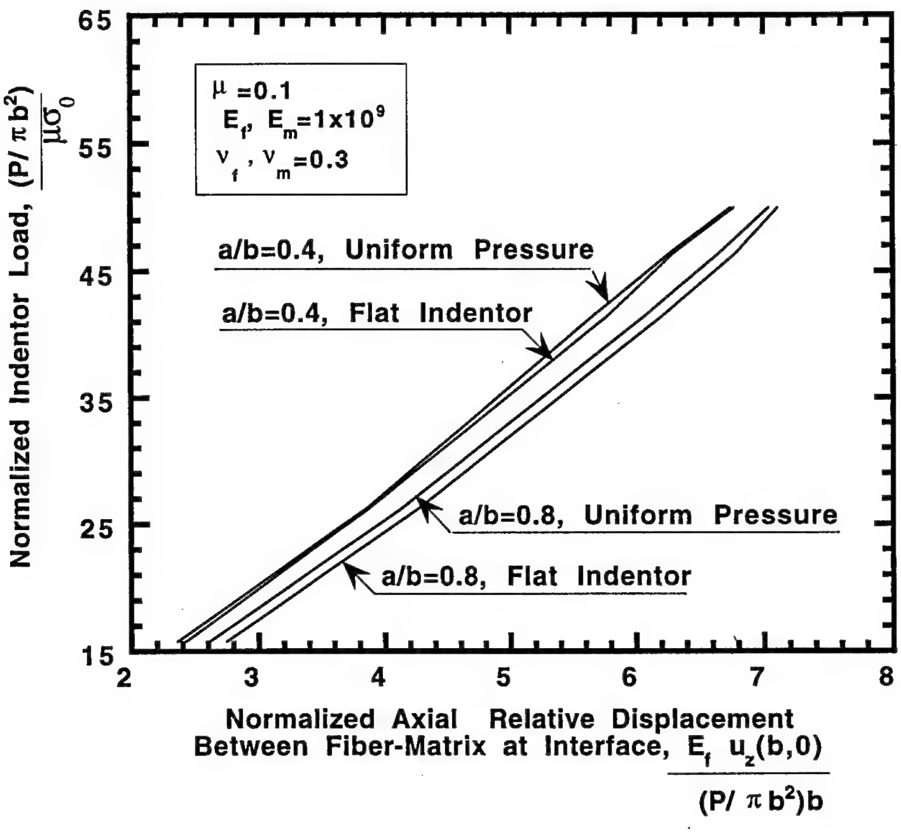

Figure 5. Indentor load as a function of axial relative displacement at fiber-matrix interface for flat indentor and uniform pressure.

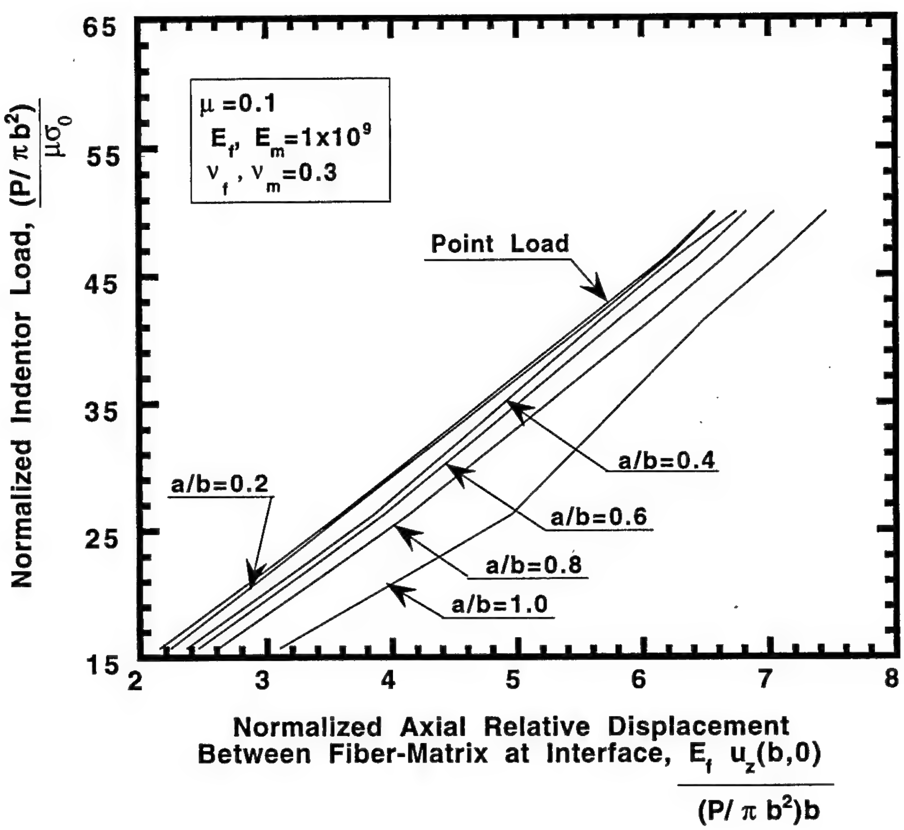

Figure 6. Indentor load as a function of axial relative displacement at fiber-matrix interface for uniform pressure.

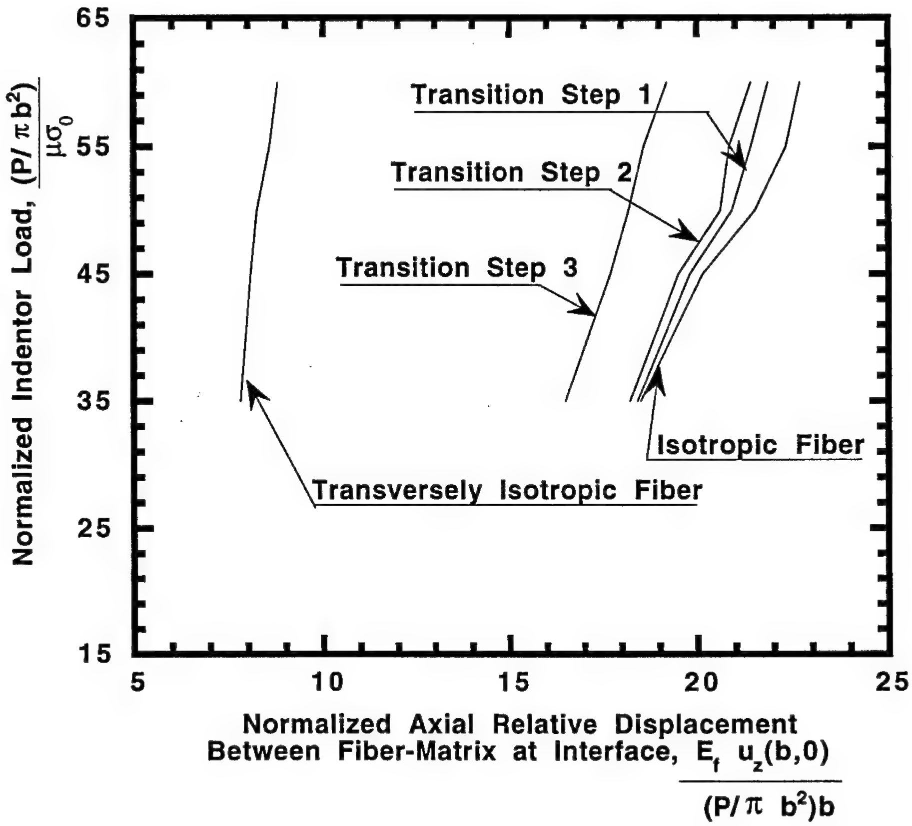

Figure 7. Indentor load as a function of axial relative displacement at fiber-matrix interface for transversely isotropic fiber.

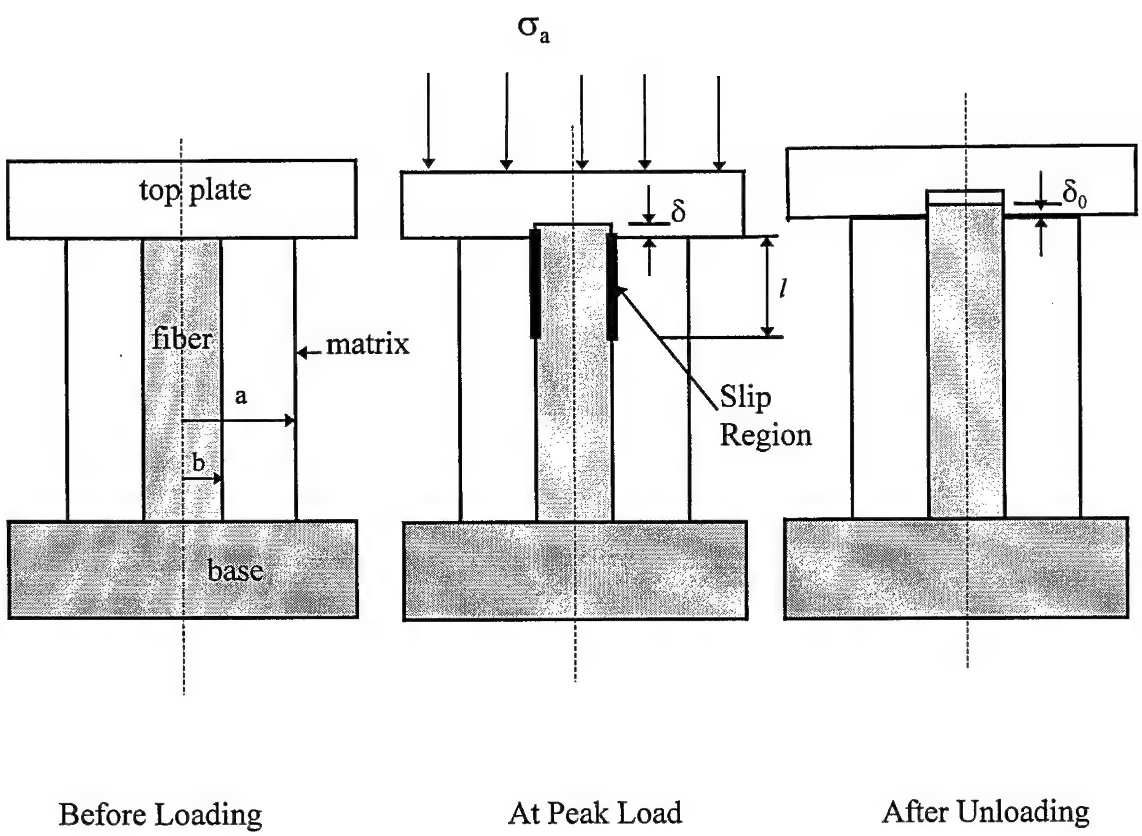

Figure 8. Schematic of the slice compression test.

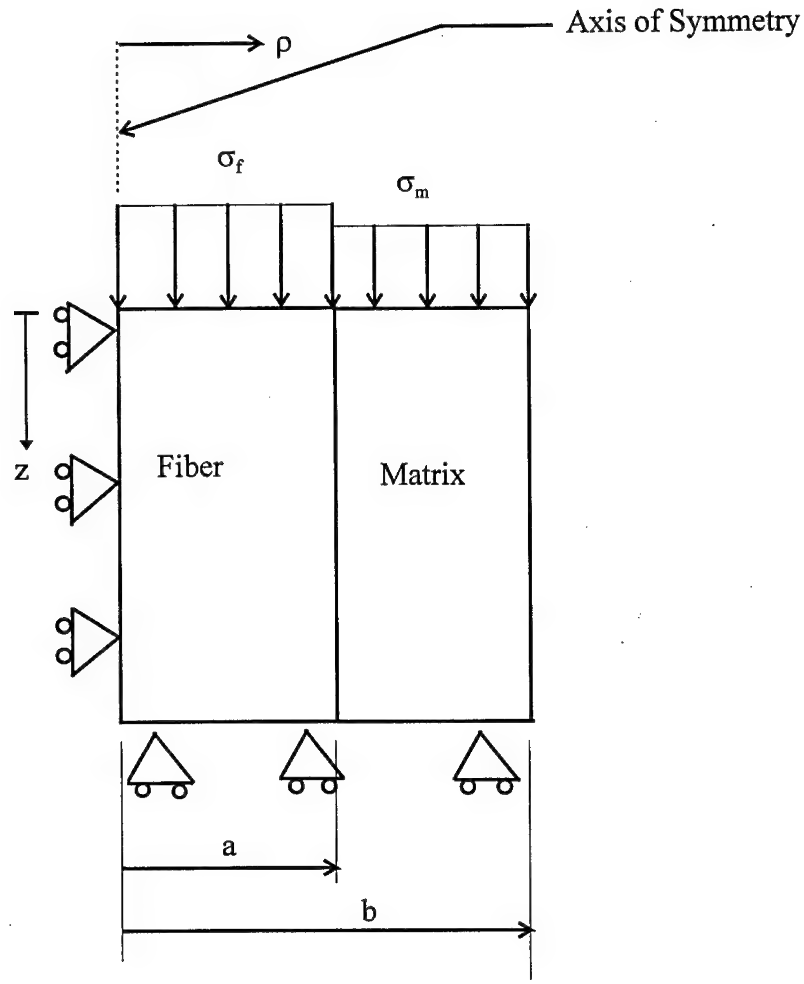

Figure 9. Boundary conditions and geometry for analytical models.

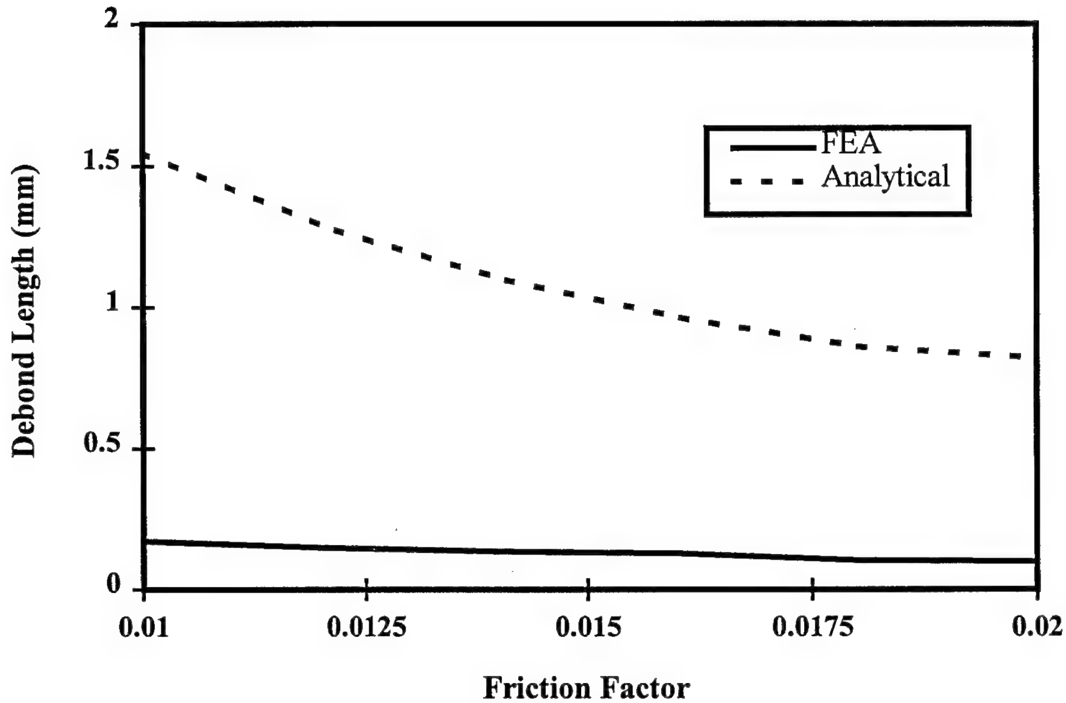

Figure 10. Variation of debond length with fiber volume fraction (net load=150 MPA, friction factor = 0.01)

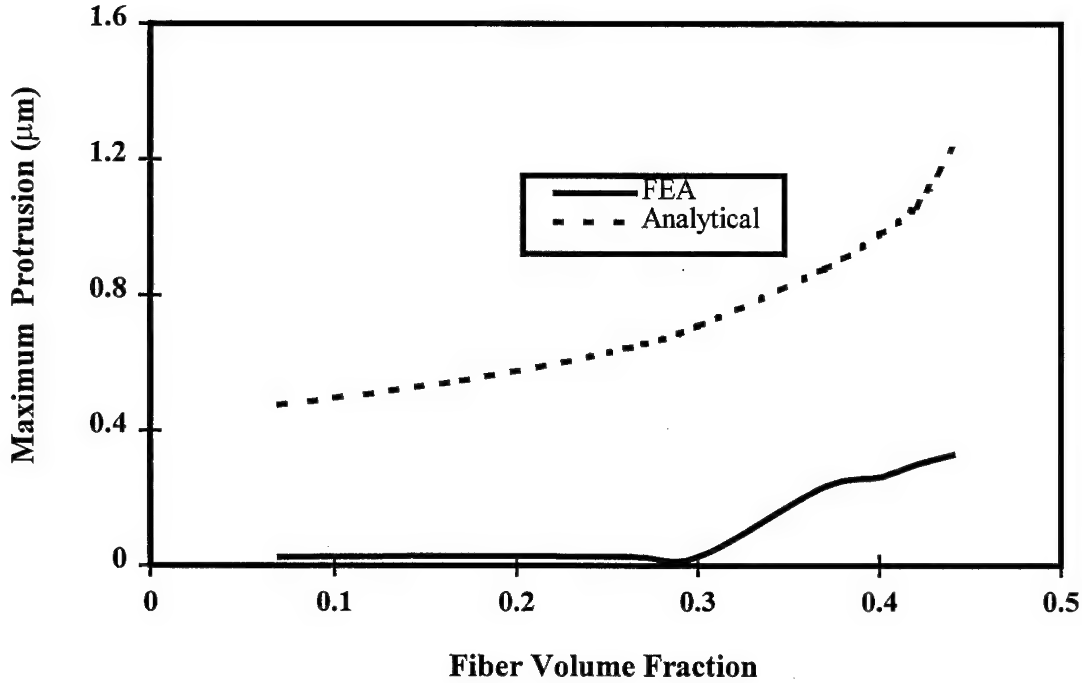

Figure 11. Variation of maximum protrusion with fiber volume fraction (net load=150 MPa, friction factor = 0.01)

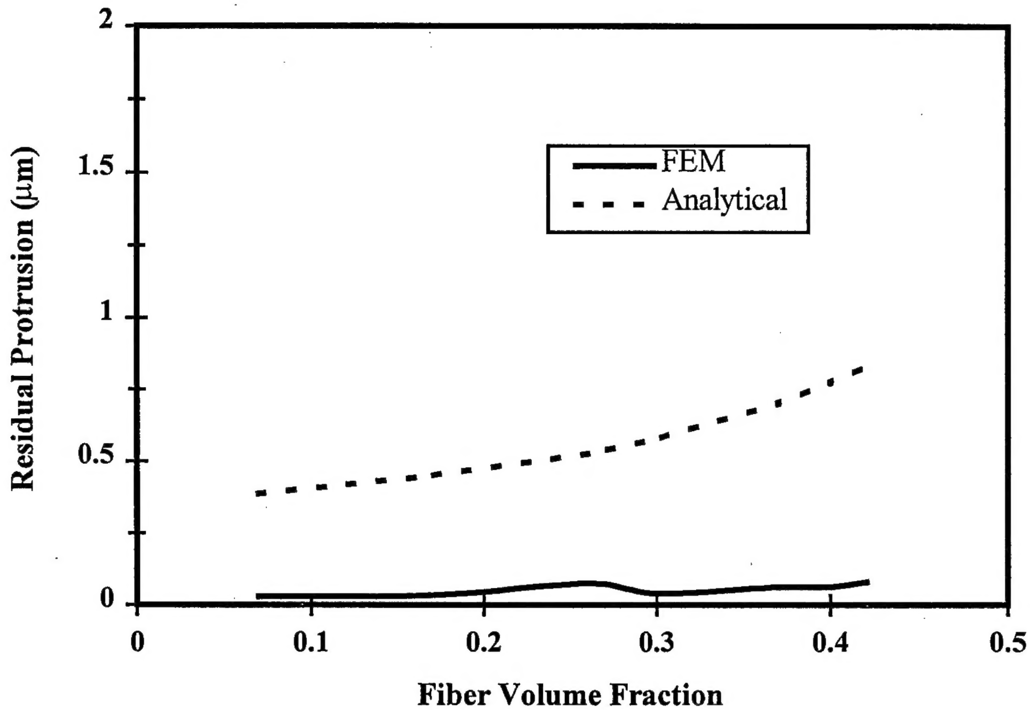

Figure 12.Variation of residual protrusion with fiber volume fraction (net load=150 MPa, friction factor = 0.01)

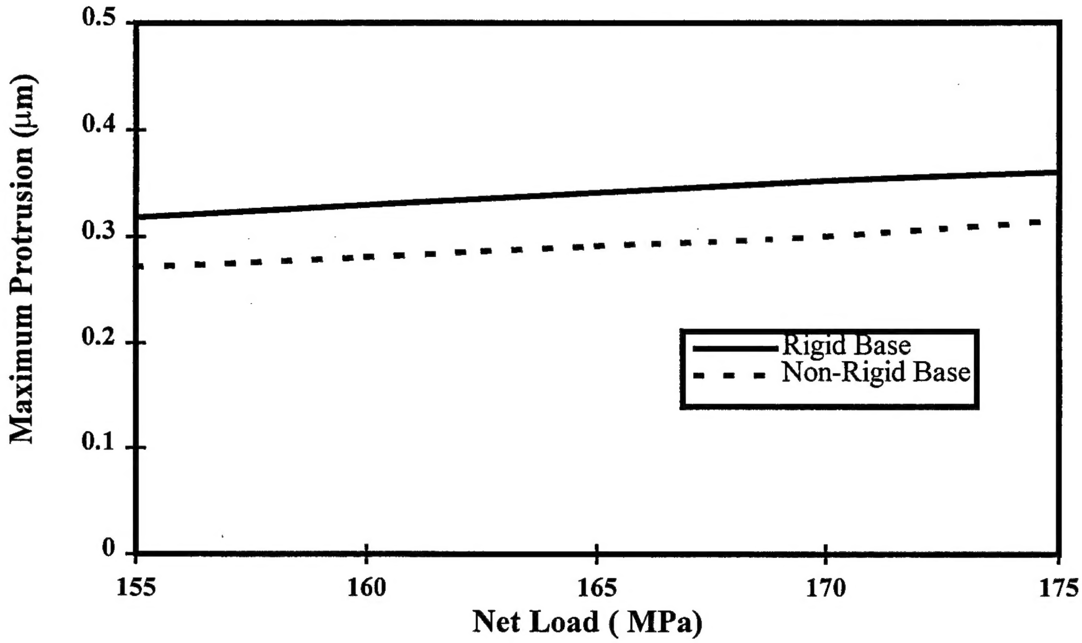

Figure 13. Effect of considering the stiffness of base in a slice compression test (friction factor=0.01, fiber volume fraction=0.44).

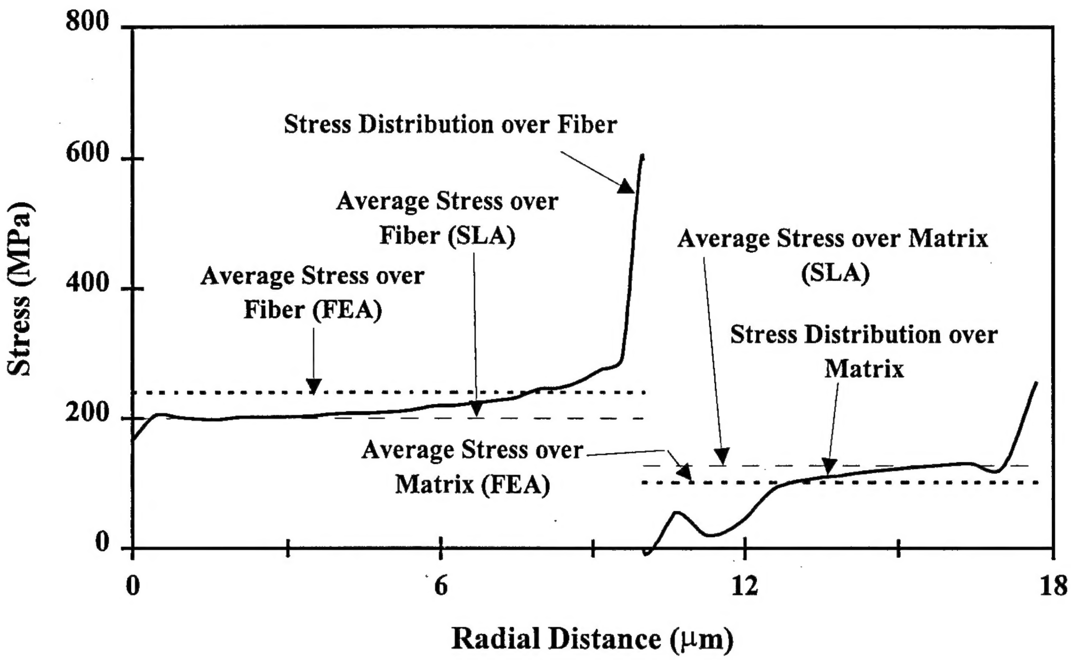

Figure 14. Stress distribution over fiber and matrix surface for a load of 150 MPa over the aluminum plate (fiber radius = 0.01 mm, fiber volume fraction =0.32)

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
October 7, 1997

3. REPORT TYPE AND DATES COVERED
Final (July 1,95-August 31, 1997)

4. TITLE AND SUBTITLE
Fracture Mechanics of Brittle Matrix Composites with Imperfect Interfaces

5. FUNDING NUMBERS
F49620-95-1-0164

6. AUTHOR(S)
Autar K. Kaw (Compiler), P. Krishnan
H. Madonraj, J. Ye, G.H. Besterfield

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of South Florida
Mechanical Engineering Department
ENB 118,
Tampa, FL 33620-5350

8. PERFORMING ORGANIZATION REPORT NUMBER
2105-060-L0

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of Defense - Air Force
AFOSR/NA, Bolling AFB, DC 20332

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
AFOSR Technical Monitor - Walter F. Jones

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

In understanding the complexity of the fracture mechanics of brittle matrix composites, knowing reliable values of the mechanical properties of the fiber-matrix interface are important. Since all experiments designed to evaluate the mechanical properties of the fiber-matrix interface rely on curve fitting experimental measurements to analytical results, accurate physical modeling of these tests is imperative. In this report, two common tests, namely the push-in test and the slice compression test, were analytically simulated. In the push-in test, the effect of factors such as indentor shape, indentor size, push-through radius hole, and transverse isotropy of fibers on load-displacement curves was studied. All factors except the push through hole-radius were found to affect the load-displacement curves. In the slice compression test, comparison was made for the values of maximum protrusion, residual protrusion and debond lengths for a simple shear-lag analysis and a finite element analysis model. Large differences ranging from 15% to 70% were found by using the two different models. Hence, the importance of accurate modeling of the test cannot be ignored. The study also gives tools to an experimentalist for designing reliable experiments for evaluating reliable values of the mechanical properties of the fiber-matrix interface.

14. SUBJECT TERMS Brittle Matrix Composites, Interfaces, Push-in, Slice Compression

15. NUMBER OF PAGES
30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102